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Citation: Appl. Phys. Lett. **89**, 171111 (2006); doi: 10.1063/1.2369818
View online: http://dx.doi.org/10.1063/1.2369818
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v89/i17
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Ultrafast electroabsorption dynamics in an InAs quantum dot saturable absorber at 1.3 μm

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(Received 11 August 2006; accepted 13 September 2006; published online 24 October 2006)

The authors report a direct measurement of the absorption dynamics in an InAs *p-i-n* ridge waveguide quantum dot modulator. The carrier escape mechanisms are investigated via subpicosecond pump-probe measurements at room temperature, under reverse bias conditions. The optical pulses employed are degenerate in wavelength with the quantum dot ground state transition at 1.28 μm. The absorption change recovers with characteristic times ranging from 62 ps (0 V) to ~700 fs (−10 V), showing a decrease of nearly two orders of magnitude. The authors show that at low applied fields, this recovery is attributed to thermionic emission while for higher applied fields, tunneling becomes the dominant mechanism. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2369818]

Over the last decade, InAs/GaAs quantum dot (QD) semiconductors have attracted considerable attention, particularly in the context of optical communications. Notably, interest in ultrafast carrier dynamics has focused on lasers[1] and optical amplifiers for applications in high speed systems.[2] Carrier capture into excited states, relaxation via carrier-carrier scattering and carrier-phonon interactions, as well as interband transitions have been well documented.[3,4] However, little effort has been devoted to the investigation of the carrier escape mechanisms relevant to QD saturable absorbers. In this letter we report ultrafast pump-probe measurements of the absorption saturation in one of these devices. The measured sweep-out times of less than a picosecond offer great potential for laser mode-locking applications. Such investigation of the dominant carrier escape and recombination mechanisms is essential to understanding the operation and limits of these devices.

Saturable absorbers comprising QD materials have been used as mode-locking elements in solid state and semiconductor lasers.[5,6] With the application of a reverse bias, subpicosecond pulses have been reported from passively mode-locked lasers (MLL) at 1.3 μm, where pulse shortening was observed by increasing the reverse electrical bias.[7,8] To date, the carrier dynamics in InAs QD *p-i-n* structures have been investigated via deep level transient spectroscopy[9] and by a combination of photocurrent and photoluminescence measurements.[10] In those studies, thermionic emission and tunneling were identified as the major escape mechanisms.

In this work, we have directly measured the field-dependent QD absorption recovery in a waveguide structure utilizing differential transmission spectroscopy (DTS). In this technique, a strong optical pulse (pump) saturates the absorption of the QD ground state transition. The transmission of a weaker pulse (probe) is then measured as a function of variable delay relative to the pump, thus mapping out the temporal dynamics of the photogenerated carriers. The resolution of this technique is ultimately determined by the pulse duration. No direct measurement of electrical transients is required, and the results are independent of the time taken for carriers to drift to the contacts. In addition, optical pumping closely resembles the application of the device as a saturable absorber.

The orthogonally polarized pump (TM) and probe (TE) pulses are produced by an 80 MHz optical parametric oscillator (OPO) with an output pulse duration of 250 fs. The sample was a *p-i-n* InAs dot-in-a-well (DWELL) waveguide structure, 1.1 mm in length with a 6 μm ridge width. Grown on a Si doped GaAs substrate, the structure is shown in Fig. 1. The active region comprised five periods of 2.5 ML of InAs, 5 nm $In_{0.15}Ga_{0.85}As$, followed by 33 nm of GaAs buffer material (to avoid electrical coupling of the dot layers). The quantum dots were 15 nm in diameter and 5 nm in height with a density in each layer of 5×10^{10} cm^{-2}. Including the active layers, the width of the intrinsic region was $d=360$ nm. Electroluminescence measurements on the sample indicated ground and first excited state transitions at 969 meV (1280 nm) and 1.046 eV (1190 nm), respectively. The OPO was tuned to the ground state transition, and with a pulse bandwidth of 7.5 meV, direct excitation to the upper state was avoided.

We carried out DTS on the above sample at room temperature for reverse applied voltages ranging from 0 to 10 V

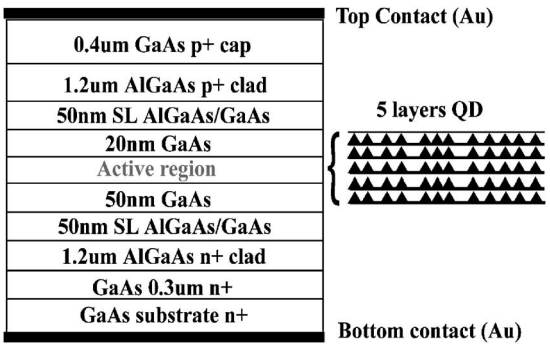

FIG. 1. Schematic depiction of the InAs (DWELL) *p-i-n* structure.

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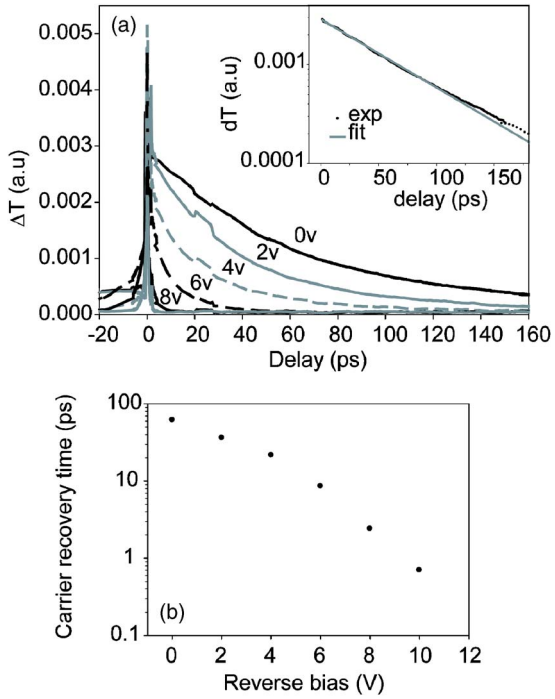

FIG. 2. Time resolved pump-probe traces for increasing reverse bias on the QD saturable absorber (a). Single exponential fit for 0 V (inset). Absorption recovery times from exponential fitting (b).

(~300 K V/cm). The measured traces are shown in Fig. 2(a). The pump pulse energy employed was 580 fJ, causing absorption saturation through band filling and giving rise to the steplike increase in probe transmission. Interestingly, we see no evidence of field screening effects in the leading edge of the traces,[11] which leads us to believe that any such effect is minimal due to the low number of carriers generated in the dots. At zero delay, the observed spike can be attributed to the interference between the overlapping probe pulses and the leaked TE component of the pump pulses.

With increasing probe delay, the transmission decays as photogenerated electrons, and holes either escape or recombine. We found that the measured absorption recoveries fit best to a single exponential of the type $\exp(-t/\tau)$ in a simple rate equation model, where τ is the recovery time [inset Fig. 2(a)]. As depicted in Fig. 2(b), the recovery time decreases by almost two orders of magnitude from 62 ps to 700 fs as the reverse applied voltage varies from 0 to 10 V. These results suggest that the dynamic response of our device is limited by one type of carrier only, in contrast to measurements reported in other QD structures with no applied bias.[12]

Figure 3 shows the measured absorption recovery rates Γ $(=1/\tau)$ as a function of applied reverse voltage. These rates can be expressed as the sum of contributions from recombination (Γ_{rec}), thermionic emission (Γ_{th}), and tunneling (Γ_{tun}) mechanisms given by

$$\Gamma = \Gamma_{rec} + \Gamma_{th} + \Gamma_{tun}. \tag{1}$$

The short recovery time (62 ps) measured at zero applied field, suggests that the contribution of recombination processes is not significant at room temperature (consistent with nanosecond recombination times as previously reported[13]).

The effect of an applied reverse field is threefold. Firstly, this causes a lowering of the barrier height by $\Delta E = E_{b0} - E_b = a|q|F/2$, where a is the dot height and q is the electron charge. F is the electric field, calculated as $F=(V+V_{bi})/d$, where V is the applied reverse voltage and V_{bi} is the measured built-in potential (≈0.8 V). Secondly, the carrier confinement energies are redshifted due to the quantum confined Stark effect. cw transmission measurements yielded a maximum ground state Stark shift of 18 meV (to which both electrons and heavy holes contribute) at 10 V reverse bias. This shift is negligible compared to the linear change in the barrier height and is therefore not taken into account in the discussion to follow. Thirdly, the applied field causes the formation of a triangular barrier. For high applied fields the width of this barrier can decrease sufficiently to allow carriers to tunnel from the ground state.

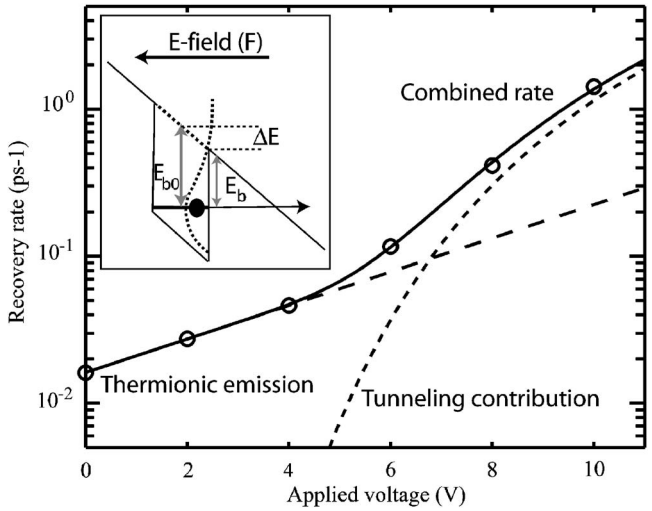

FIG. 3. Rate equation fitting for pure thermionic emission, tunneling, and the combined carrier escape rate from the ground state. Schematic showing the physical mechanisms (inset).

At low bias, tunneling processes are highly improbable and thermionic emission is expected to be the dominant carrier escape mechanism. We assume a common thermally activated emission rate equation[14] modified only by the linear reduction in the barrier height,

$$\Gamma_{th} = \Gamma_0 \exp\left[\left(\frac{aqV}{2d}\right)\frac{1}{kT}\right]. \tag{2}$$

Here, Γ_0 is the rate for no applied voltage ($V=0$) and k and T are the Boltzmann constant and absolute temperature, respectively. In Fig. 3, only the first three data points fit satisfactorily to an equation of the form $A\exp(BV)$. This yields $B=0.263\pm0.019$ V^{-1}, in excellent agreement with the expected linear reduction of the barrier height (≈0.278 V^{-1}), thus justifying our assumptions regarding the Stark shift and the recombination rate. It can be seen that this fit diverges for applied biases beyond 4 V, suggesting a significant contribution from an additional escape mechanism.

The escape rate corresponding to tunneling processes in the applied field direction can be calculated as the product of barrier collision frequency[15] and transmission probability through such a barrier. The latter was estimated via a one-dimensional WKB approximation, giving the following expression:

$$\Gamma_{tun} = \frac{\hbar\pi}{2m_d^* a^2}\exp\left(-\frac{4}{3}\frac{\sqrt{2m_b^*}E_b^{3/2}}{q\hbar F}\right). \tag{3}$$

Here, m_d^* and m_b^* are the effective masses in the dot and buffer materials, respectively, and E_b is the barrier height. Using the previous fit at low applied voltages, the thermionic contribution was subtracted from the total measured rates. The remaining contribution was then fitted to Eq. (3). The field dependence of Γ_{tun} is most heavily weighted by the $1/F$ factor in the exponential transmission term, so we assume a constant barrier height E_b in our fit. We use this approximation to highlight the basic physical trend of the tunneling mechanism. The fit yields a barrier collision frequency of 395 ps^{-1} from which we estimate an effective mass in the InAs dot to be 0.02 m_0, where m_0 is the free electron mass. Within the simplicity of our model, this leads us to believe that the dynamics observed in our measurement can be attributed to the electrons.

Figure 3 illustrates how the individual contributions of thermionic emission and tunneling dominate in the regions of low and high fields, respectively. Also, note that the sum of these two contributions $(\Gamma_{\text{th}}+\Gamma_{\text{tun}})$ gives an excellent fit to the measured rates across the entire range of applied voltages. We believe our measurements are not resolving the very fast hole dynamics. Previously reported band offset ratios[16] indicate that even at low fields the thermionic emission of holes would be well over one order of magnitude faster than that of electrons. In addition, at larger electric fields, it is likely that the hole bound states merge with the continuum due to the lowering of the barrier.

In summary we have directly measured, by optical means, the electron escape time from the QD ground state in a reverse biased *p-i-n* structure. Absorption recovery times at room temperature ranging from 62 ps (0 V) to 700 fs (−10 V) were found, showing a decrease by nearly two orders of magnitude. We have given strong evidence that tunneling is responsible for the shortest absorption recovery times, in excellent agreement with previously reported trends observed in MLL. Absorption recoveries on the order of a picosecond are capable of producing sub-100-fs pulses by passive mode locking.[7] This should also prove useful in the development of subpicosecond electroabsorption modulators for switching above 1 THz.

One of the authors (D.B.M.) would like to thank EPSRC for financial support of his studies.

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